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# Galaxies and Overmerging: What Does it Take to Destroy a Satellite Galaxy?

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**Abstract.** The Ultra Compact Dwarf (UCD) galaxies recently discovered in the Fornax and Virgo clusters exhibit structural similarity to the dense nuclei of nucleated dEs indicating that the progenitor galaxy and its halo have been entirely tidally disrupted. Using high resolution $N$-body simulations with up to ten million particles we investigate the evolution and tidal stripping of substructure halos orbiting within a host potential. We find that complete disruption of satellite halos modeled following the NFW density profile occurs only for very low values of concentration in disagreement with the theoretical predictions of CDM models. This discrepancy is further exacerbated when we include the effect of baryons since disk formation increases the central density.

## 1. Introduction

High resolution numerical simulations and sophisticated semi-analytic modeling have significantly improved our understanding of the properties and the evolution of cold dark matter (CDM) substructure. It has been demonstrated (Moore et al. 1998, Colpi, Mayer, & Governato 1999; Moore et al. 1999; Klypin et al. 1999; Taffoni et al. 2003) that tidal distruption is very inefficient for these low mass subhalos. Satellites represent earlier generations of the merging hierarchy and are typically denser and more concentrated than their more massive hosts. While gravitational tides serve to unbind mass associated with these subhalos, it is still not clear whether or not complete disruption of substructure halos can take place in a CDM potential.

Direct evidence of tidal disruption processes operating effectively within galaxy clusters has recently been provided by the discovery of a new population of subluminous and extremely compact objects in the Fornax (Drinkwater et al. 2000; Phillipps et al. 2001) and Virgo (Drinkwater, private communication) clusters. These Ultra Compact Dwarf (UCD) galaxies are dynamically distinct systems with intrinsic sizes $\lesssim$100 pc, and properties, including velocity dispersions, absolute magnitudes and mass-to-light (M/L) ratios, considerably higher than any normal globular cluster (Drinkwater et al. 2003). There is accumulating evidence that the UCDs constitute the remnant nuclei of dwarf galaxies whose extended stellar component and DM halo have been both entirely disrupted by gravitational interactions within their host cluster. Their derived M/L ratios range from 2 to 4 and are consistent with those of stellar populations

suggesting that these systems contain no dark matter. Other factors consistent with the interpretation that the UCDs are the products of tidal disruption processes include their strong structural similarity to the dense nuclei of nucleated dwarf ellipticals (dEs) and the lack of extended stellar envelopes around them in photographic images (Phillipps et al. 2001).

Our goal is not only to investigate how probable complete disruption of substructure halos at the typical distances of known UCDs (within about 30% of the cluster virial radius) is, but also to place constraints on the structure of DM halos and examine whether the existence of the UCDs is consistent with the theoretical predictions of CDM models.

## 2. Numerical Simulations

We study the evolution of dwarf satellites comparable in mass to typical cluster nucleated dEs in the external potential of the Fornax cluster. The NFW density profile (Navarro, Frenk, & White 1996) is used for both the live satellites and the spherically symmetric static host potential. The latter represents a cluster halo with virial mass $M_{\rm prim} = 0.5 \times 10^{14}\, h^{-1}{\rm M}_\odot$ and $c_{\rm prim} = 8.5$ (hereafter, $h = 0.5$). The satellite's virial mass is $M_{\rm sat} = 2 \times 10^{10}\, h^{-1}{\rm M}_\odot$. Our simulations neglect the effects of dynamical friction and the response of the primary to the presence of the satellite. Considering the vast difference in the mass and size of the two main systems we do not expect our results to be affected by this choice. In this investigation all satellite models are Monte Carlo realizations of the exact phase-space distribution function under the assumptions of spherical symmetry and isotropic velocity dispersion tensors, $f = f(E)$. Kazantzidis, Magorrian, & Moore (2003) have explicitly demonstrated that the choice of initial conditions is vital for studies like the present. Out of equilibrium initial conditions may artificially accelerate the mass loss of the model satellites by decreasing their central density and changing the character of their orbital anisotropy.

The current positions of the UCDs which give an indication of the apocenter of their orbits coupled with theoretical studies of halo orbital properties, will be used to constrain the orbital parameters of the satellites. In particular, we shall adopt an apocenter radius equal to $r_{\rm apo} = 1.77\ R_{\rm s}$, where $R_{\rm s}$ is the scale radius of the host halo and $(r_{\rm apo}/r_{\rm peri}) = (5{:}1)$ close to the median ratio of apocentric to pericentric radii found in cosmological simulations (Ghigna et al. 1998). The pericenter of the orbit is 50 kpc in all the simulations presented here. We evolve our models using PKDGRAV (Stadel 2001) for 10 Gyr. In all our runs, the total energy was conserved to better than 0.1%. In Figure 1 (left panel) we perform a quantitative comparison of the evolution of the bound satellite mass for three different mass resolutions. We use the group finder SKID (Stadel 2001) to identify the remaining bound mass. We define complete disruption of a satellite system when we do not find any gravitationally bound structure at a scale of $2\varepsilon_s$ or larger, where $\varepsilon_s$ is the gravitational softening for our runs. The satellite halo has a $c_{\rm sat} = 5$ and is simulated with $N = 10^5$ (filled squares), $N = 10^6$ (open circles), and $N = 10^7$ (filled circles) particles. The evolution of the bound mass is plotted up to the point where complete disruption of the satellite system occurs. The halo resolved with just $10^5$ particles fully disrupts after just two orbits, but this is clearly a resolution effect since the same halos resolved with

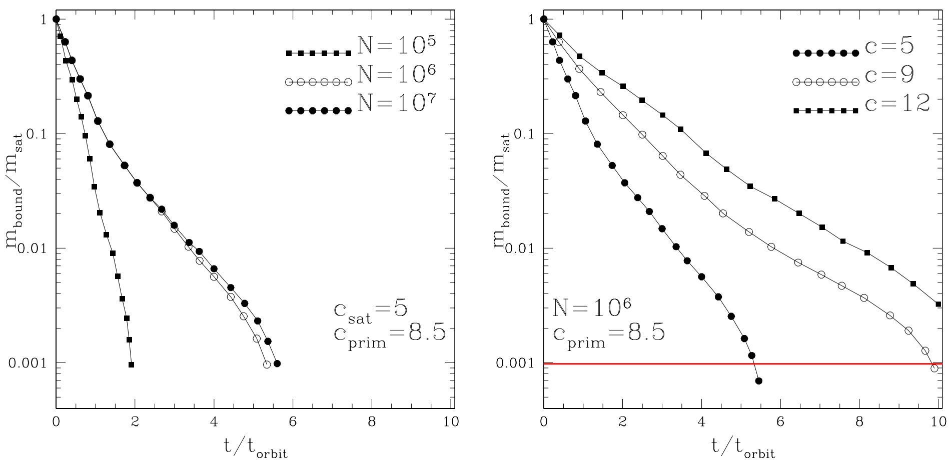


Figure 1. Left: Bound satellite mass as a function of the orbital period for three different mass resolutions. Results approach convergence when adopting a mass resolution of the order of a few million particles. Right: Evolution of the bound NFW satellite mass for three different concentrations. The value $c_{\rm sat} = 9$ gives the upper limit for disruption at the timescales of interest.

more particles survive significantly longer. Convergence is achieved when we adopt a mass resolution of more than $10^6$ particles per halo.

In order to avoid an unecessary computational cost, we adopt a mass resolution of $N = 10^6$ in the following runs. We set the gravitational softening to $\epsilon = 50$ pc, hence, our force resolution being equal to $2\varepsilon$ corresponds roughly to the upper limit inferred for the UCD size. At this force resolution only completely disrupted systems might be suitable UCD progenitors. In the right panel of Figure 1 we demonstrate that the satellite with $c_{\rm sat} = 9$ defines the upper limit of the concentration parameter for disruption at the timescales of interest. Note that the thick horizontal solid line denotes the region below which the halo may resemble that of a UCD galaxy. Satellites with lower values of concentration disrupt earlier and therefore could be associated with UCD progenitors. These values are significantly lower than those measured in cosmological simulations for halos in these mass scales (Bullock et al. 2001).

## 3. The Effect of Baryons on Satellite Survival

The theoretical predictions of CDM models for the concentration values are only for precollapse halos. A real galaxy would always have an "effective concentration", $c_{\rm eff}$, higher than that of a pure DM halo system. The baryons steepen the inner density profile by both adding mass to the center and causing the halo to adiabatically contract responding to their infall, increasing considerably the resilience of satellites to tidal stripping. In Figure 2 we present the rotation curves of two disk models constructed using the semi-analytical modeling of Mo, Mao, & White (1998) together with the rotation curve of a pure DM halo with concentration equal to the upper limit of disruption ($c = 9$) for the adopted standard

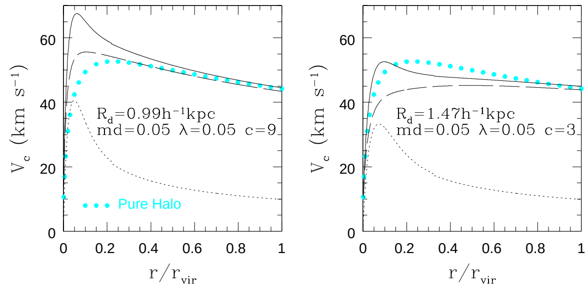


Figure 2. Rotation curves of disk models with the same typical values for $m_{\rm d}$ and $\lambda$. Left: A typical disk galaxy with $c_{\rm halo} = 9$ has a significantly higher $c_{\rm eff}$ than a pure DM halo with the same concentration. Right: The correction due to the presence of baryons yields $c_{\rm halo} = 3$ for the starting halo concentration of this disk model.

orbit. Both models have typical values of the disk mass fraction $m_{\rm d} = 0.05$ and halo spin parameter $\lambda = 0.05$. In the left panel is illustrated that a typical disk greatly increases the effective concentration of a pure DM halo making the disruption of a satellite galaxy significantly more problematic. In order to achieve an effective concentration of $c_{\rm eff} \leq 9$ we need to start from $c_{\rm halo} < 3$ for the same typical disk parameters (right panel). This value is more than 4 $\sigma$ lower than the theoretical predictions for the mass range of our satellites.

We are unable to explain the origin of the UCDs within the CDM models. We shall explore further the dependence of satellite disruption on their orbital properties, central density slopes, and host halo structure to address this issue in more detail (Kazantzidis, Mayer & Moore, in preparation).

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